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Damage to Large Optics by Focusing Acoustic Transients

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DISCLAIMER

ACOUSTIC DAMAGE TO LARGE-APERTURE OPTICS*

by

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Abstract

We have observed damage to 80-cm-diam fused-silica disks and lenses subjected to high-fluence pulses (up to 2.3 J/cm^2) from an upgraded Nova laser beamline (wavelength 351 nm; pulse duration 2.35 ns; beam diameter 70 cm; energy up to 8 kJ). Damage occurred in the center of each element, where a 6-cm-wide obscuration prevented direct illumination. We believe that light strongly scattered by transverse stimulated Brillouin scattering (SBS) interacts with the surface and with the bulk of the substrate, producing two kinds of acoustic waves that propagate to its center, where they become strong enough to do damage.

In the surface interaction, scattered light is absorbed by an O-ring near the perimeter of the optic, creating a Rayleigh wave that propagates along the surface to the center of the optic. The resulting damage takes the form of crater-shaped fractures about 8 mm in diameter and 4 mm deep.

In the bulk interaction, transverse SBS strongly compresses the optic in large regions transverse to the direction of beam polarization at the perimeter of the beam. The compression may result from electrostriction: the SBS intensity is several times that of the incident beam. Compressive waves resulting from the relaxation of these regions propagate to the perimeter of the optic, where they are reflected as bulk tensile waves. The focusing of these tensile waves in the center of the optic results in cracks along the direction of polarization.

Up to 25 percent of the incident beam energy is lost to SBS at these high fluences. Frequency chirping of the laser beam by 45 GHz strongly suppresses the SBS, and reduces the amplitude of the stress waves by about an order of magnitude; no energy loss, cratering, or cracking occurs under these conditions.

We propose design rules for avoiding acoustic damage in large optics and compare observed thresholds for transverse SBS with predictions in the literature.

Introduction

The Nova laser system is being upgraded with platinum free phosphate glass, which will allow higher fluences without damage to the amplifiers[1]. In order to determine the improved performance of the laser with the new glass, a prototype beamline was built and tested. Last February, after a 2.4 ns shot at 5.9 kJ at 0.35μm, a 5 cm long straight crack appeared in the center of an 80 cm diameter, fused quartz, diagnostic beamsplitter where no light had been incident. Direct illumination of this area is prevented by a 6 cm wide stripe obscuration. This obscuration is necessary to protect the disk split in the largest amplifiers, which is necessary to suppress parasitic oscillation. Close examination of the fracture revealed two small craters on the incident and exit surfaces of the beamsplitter. Curved hackle marks indicated that the linear crack had initiated from the two craters nearly simultaneously, joined at the center plane of the optic, propagated away from the central region and abruptly stopped. It was soon noted that the linear crack was closely aligned with the polarization direction of the 0.35μm light, which is oriented 35 degrees from the polarization of the 1μm fundamental beam.

Additional shots established that no stray reflections or ghost foci could be detected on the incident or exit side of the beamsplitter near its center. A review of photographs taken of three large optics which had been damaged while on the Nova ten beam target chamber in the previous year and a half revealed similar linear fractures aligned with the 0.35μm polarization. All of the damaging shots had occurred on high energy 0.35μm pulses of about 3 ns duration. We believe that we now understand most of the processes that cause this type of damage, which is the subject of this paper.

It is important to note that SBS in optics has been expected for some time. About 20 years ago, John Emmett and Art Schawlow published a study of transverse SBS in liquids, including observations of multiple SBS shifts and transverse filamentation[2]. Ten years ago, LLNL supported a study on SBS gains in optical glass on the suspicion that it would eventually be important[3]. And more recently, LANL has funded a modeling effort of transverse SBS in fused silica at Spectra Technology[4].

At high fluences in large optics it is possible to exceed the threshold for generation of stimulated Brillouin scattering transverse to the direction of propagation. This scattered light can be absorbed by support materials, giving rise to surface waves. When the SBS intensities get sufficiently large, strong bulk waves are also generated. Because of strong high frequency attenuation, the SBS acoustic waves last only about a nanosecond longer than the incident pulse, whereas the acoustic waves generated from energy deposition on supports or by the relief of electrostrictive compression from intense SBS last many hundreds of microseconds. These waves can focus within the optic from reflection at the free surfaces to create stresses which fracture the substrate.

In addition to the optical damage, we have observed up to 25% energy loss from the laser beam due to SBS. Without proper SBS supression, transverse energy loss will become very large.

We have instrumented both a full aperture beamsplitter and a Nova focus lens in experiments to study SBS. A distinction as to which optic the particular experiment used will be made only where it is important. We will discuss surface waves and our evidence for them, bulk waves in the substrate and energy loss from the beam, and finally a solution to the SBS problem, along with some suggestions for avoiding acoustic damage in large optics will be discussed.

Simple Theoretical Model

Transverse SBS at 350 nm in fused silica generates acoustic phonons at a frequency of 35 GHz. Phonons at this frequency have a measured[3] linewidth of 160-170 MHz or an intensity decay time of about 1 ns. Therefore, the SBS gain will be transient for pulses shorter than a few nanoseconds. The growth of SBS under these conditions is best treated by numerical integration of the propagation equations[4], but there is a simple model, as shown here, which is useful for understanding general scaling properties.

The intensity of the light scattered by SBS achieves maximum gain for a scattered wave polarized parallel to the pump, with a typical dipole (cosine squared) dependence on the angle between these polarizations. The steady-state gain for parallel polarizations is[5] e^G where

$$G = \gamma I L \tag{1}$$

and

$$\frac{\gamma}{\tau} = \frac{4\pi^2 \gamma_e^{\,2}}{\lambda_p^{\,2} c V_a} \sin(\theta/2) \tag{2}$$

In this expression, γ_e is the electrostrictive constant $\rho\partial\varepsilon/\partial\rho$, V_a the velocity of the acoustic wave, λ_p the vacuum wavelength of the pump, θ the angle between the pump and scattered wave propagation directions, and τ the time constant for the decay of the acoustic wave intensity. The time constant τ is a function of the acoustic frequency.

One can show[6] that when the gain exponent, $G \gg 1$ and $t/\tau \ll G$, laser pulselengths less than about 5τ are reasonably well described by a transient scattering model which assumes very short pulses. This model gives a gain exponent $G(t)$ at time t into a square pulse of intensity I and interaction length L as

$$G(t) = 2\,[(\gamma/\tau) I L t]^{1/2}\ . \tag{3}$$

Note that the gain depends on the integrated fluence $\int I dt$ up to time t and on the ratio γ/τ, which is the integrated linestrength of the Brillouin line. In the transient limit, the Brillouin linewidth $1/2\pi\tau$ and the pulseshape of the optical pulse are unimportant.

The transient gain parameter γ/τ is proportional to $1/\lambda_p^2$, so transient SBS is most important at short wavelength. The $\sin(\theta/2)$ dependence shows that the preferred direction for transient SBS is backward ($\theta = \pi$); however, in thin components there is not enough pathlength in this direction to give high gain. The transverse gain at $\theta = \pi/2$ is down by only a factor of $1/\sqrt{2}$. Also, angles slightly greater than $\pi/2$ may be favored in moderately thick components.

SBS acoustic waves grow for a time t, and the scattered optical wave grows during propagation over a distance L which can be replaced by a growth time $t_g = nL/c$. The maximum value which t_g can take is the pulselength t of the laser pulse. If the scattering is transverse, then the pump beam aperture may set a smaller limit to t_g.

At some value of G(t), usually estimated to be about $G_T = 25$-35 nepers, the intensity of the scattered wave will reach a significant fraction of the pump wave intensity. A small increment in gain above this value will take the scattering into the regime of pump depletion, in which this small signal model breaks down and the reflection coefficient from the acoustic wave approaches unity. We shall define this point as an SBS "threshold". Assuming that the intensity I is constant across the beam aperture, we can define a threshold parameter at any point in the aperture

$$H(t) = Itt_g = \frac{G(t)^2\, n\tau}{4\, c\, \gamma} \tag{4}$$

For H(t) less than the threshold value H_T set by substituting G_T into Eq. 4 there will be no SBS loss; above that value the SBS reflectivity will approach 100 percent.

The threshold value G_T has a weak dependence on the thickness of an optical component. At a particular value of G(t) there will be a constant side-scattered intensity per unit thickness, so a thick component obviously has a slightly larger total loss at a particular G(t) and a lower "threshold" G_T.

Surface Waves

Strain gages have been used to detect surface waves generated by blowoff from an O-ring support on an 80 cm diameter Corning 7940 focus lens. The strain gages were located along a radius in the disk split obscuration. Because the surface wave is focusing as it propagates toward the center of the optic, its amplitude increases dramatically as shown in Fig. 1. A position-time plot of each channel is shown in Fig. 2. The wave speed of 3.45 mm/μsec corresponds to a Rayleigh wave in fused silica. This type of surface wave, first investigated by Lord Rayleigh in 1887, has both shear and longitudinal components. At 5.56 kJ this type of wave caused an 8 mm diameter, 4 mm deep, crater in the center of the output sideof the lens. The depth is consistent with the location of the maximum stress level produced by a Rayleigh wave (one-quarter wavelength below the surface). Frequency analysis of this wave indicated its frequency was 240 KHz, which corresponds to a wavelength of about 15 mm. Thus the bottom of the crater corresponds to about the depth of maximum stress. The peak stress at the surface as detected by strain gages for various energies and radial locations are shown in Fig. 3. There is a roughly $1/\sqrt{r}$ dependence of the peak stress measured by the strain gages as the wave focuses. At first, it is surprising that a nonlinear scattering process causes a nearly linear variation of the stress level with energy. However, the SBS gain rises very quickly during the later part of the square pulses that we used, and as the fluence is raised, the threshold is exceeded earlier in the pulse. That is, Eq. 4 is a good approximation of our experiments. There was no damage to the input side of the lens. We think this is due to the lens design, which has a 25 mm wide annular groove in this face designed to prevent internal optical reflections from focusing within the lens. This groove also prevents the propagation of surface acoustic waves to the center.

When only short sections of the focus lens O-ring were used for support, the Rayleigh wave amplitudes were reduced by more than a factor of two. However, these surface waves were still present at small amplitudes. Surface absorption in the sol-gel coating may be responsible for the small residual stress wave.

Bulk Waves

Bulk waves (i.e., bulk shear and longitudinal waves) are difficult to study using surface mounted strain gages, so our diagnostics are less convincing than for the surface waves. However, large signals on perimeter strain gages suggest that large areas in the substrate in the perimeter region of the beam are in a highly compressed state after a high fluence shot where SBS has been produced. Modeling of the strain relief process shows that a compressive strain would produce a longitudinal wave which propagates to the circular perimeter of the substrate, where it is reflected as a symmetric tensile wave. This tensile wave then propagates into the center of the optic with increasing amplitude as it focuses.

The large tensile waves arrive at the center of the optic after the surfaces have already been cratered by surface waves, which greatly reduces the stress required for extending the fracture. That the source of the resulting fractures is associated with the regions having high SBS compression is supported by the fact that the linear cracks are aligned with the 0.35μm polarization, which is normal to the maximum transverse gain direction for SBS.

Energy Loss

The side scattered light from the beamsplitter and focus lens was monitored with a high speed photodiode and oscilloscope system which has a rise time of 80 ps. The incident and transmitted laser beam was recorded by a LLNL streak camera with 40 ps response. The signals from these on a 5.76 kJ, 2.35 ns, 0.35μm shot are shown in Fig. 4. Note the exponential rise of the side scattered light and the deep depletion of the tail end of the transmitted pulse. Analysis of the exponential rise of the side scattered light signals for five shots that had good signal to noise ratio gives gains in nepers/ns as shown in Table I. Note that these gains are apparent gains as seen from the transverse direction. Their values are complicated by field view and integration in the transverse direction and are therefore not the same as the exponential gains of Eq. 1.. The data in Table I are all pulse durations of 2.35 ns. The gain path length differed by 9 cm due two different polarization orientations which caused the maximum SBS gain path to cross the disk split obscuration at an angle. The data show that this gain path length is significant. These different orientations were the result of using two different KDP conversion crystal arrays.

When the SBS threshold is greatly exceeded, the side scattered intensity can exceed the intensity of the incident beam, since the scattered light can have comparable fluence with a shorter pulse duration as demonstrated in Fig. 4. This leads to filamentation and severe self-focusing, which implies intense electrostrictive compression in these regions. The signature of the filamentation is damage in the form of long chains of fine bubbles aligned with the SBS preferred direction. The total energy that is lost to SBS processes has been determined by incident and transmitted calorimetry as shown in Fig. 5.

A summary of the 0.35μm fluences and pulse durations where we have observed damage are shown in Fig. 6. Also shown is the boundary between safe and damaging operations, which corresponds to a fluence pulse duration product of 3.7 J-ns/cm^2. This boundary is in reasonably good agreement with the theoretical work on transverse SBS by Eggleston and Kushner cited earlier. This figure also indicates the performance limits that have recently been demonstrated on the Nova prototype beamline. Clearly, for pulse durations in excess of 1.8 ns, we must restrict the third harmonic energy levels or suppress SBS.

Chirping

The review of broadband SBS (where the laser linewidth is large, compared to the Brillouin linewidth) studies by George Valley[7] concludes that broadband has substantially lower SBS gain. However, implementation of broadband input to the Nova amplifier chain with an acceptably low amplitude modulation is a difficult matter. We chose to pursue chirping of the narrow band oscillator with frequency shifts that are fast compared to the transient SBS gain build-up times.

A lithium niobate phase modulator was used to chirp the 1μm beam. The amplitude modulation with this technique was less than 20 percent. A sinusoidal chirp, having a peak-to-peak amplitude of 15 GHz, completely suppressed the SBS in the beamsplitter. Note that the chirp at the third harmonic is three times as great. Side scattered light and acoustics were observed at the noise level of the detectors and no discernable energy was lost from the beam. The relative intensity of the side scattered light for chirped and unchirped shots are shown in Fig. 7. Acoustic emission signals are similarly shown in Fig. 8. A single shot, done with 8 GHz chirp of the fundamental frequency, appears to have been almost as effective as the 15 GHz chirp. These data points are indicated on the above figures. At present, we only know that the chirp should be large, compared to the 165 MHz SBS linewidth. Chirp bandwidth of less than 15 GHz at 1μm, which gives 45 GHz at 0.35μm, does not degrade the harmonic conversion efficiency by more than one percent.

Suggested Design Considerations

Designers of large aperture laser optics should keep the following points in mind. These suggestions are especially important when working with visible or UV laser systems with high fluences.

- Avoid acoustic foci within optics - do not allow symmetric acoustic sources or reflections.
- Protect support material from scattered light.
- Check SBS thresholds for new systems.
- Consider chirping or aperture division if SBS appears possible.

Chirping appears to work well for our particular situation, but we have yet to explore the chirp required for pulses longer than about 2.5 ns. Chirping will suppress the onset of SBS, but it will not eliminate it. At a sufficiently high fluence level the SBS gain will become a problem for any given level of chirp.

Acknowledgement

The entire Nova laser operations staff contributed to these experiments and deserve credit for a job well done.

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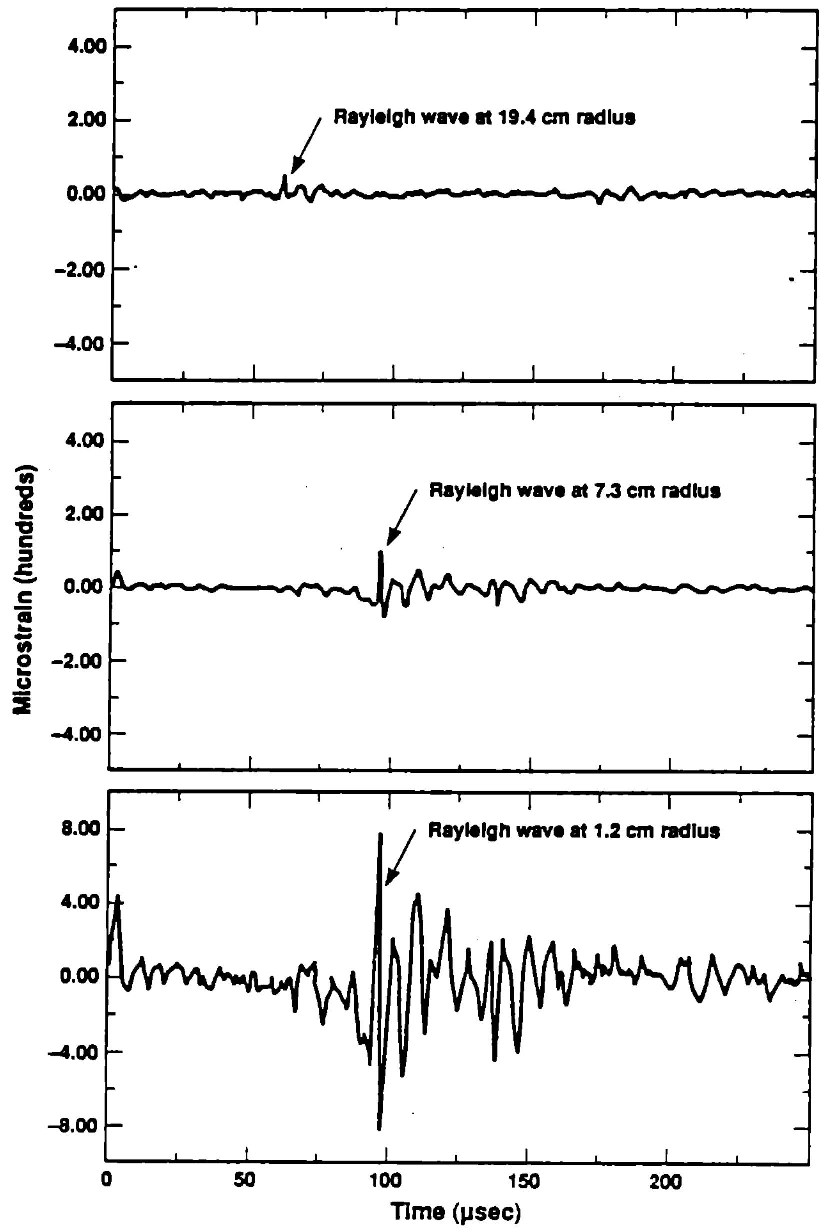

Fig. 1 Strain gage records of Rayleigh wave focusing at the center of a focus lens.

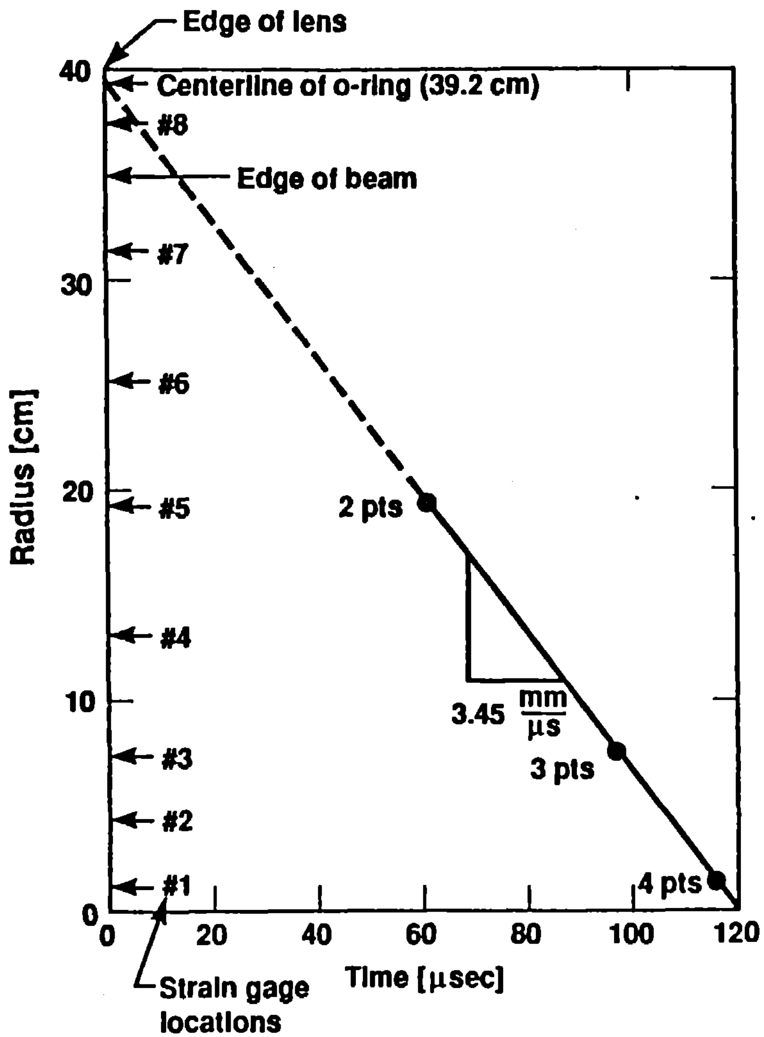

Fig. 2 Position-time plot of Rayleigh wave from strain gage data.

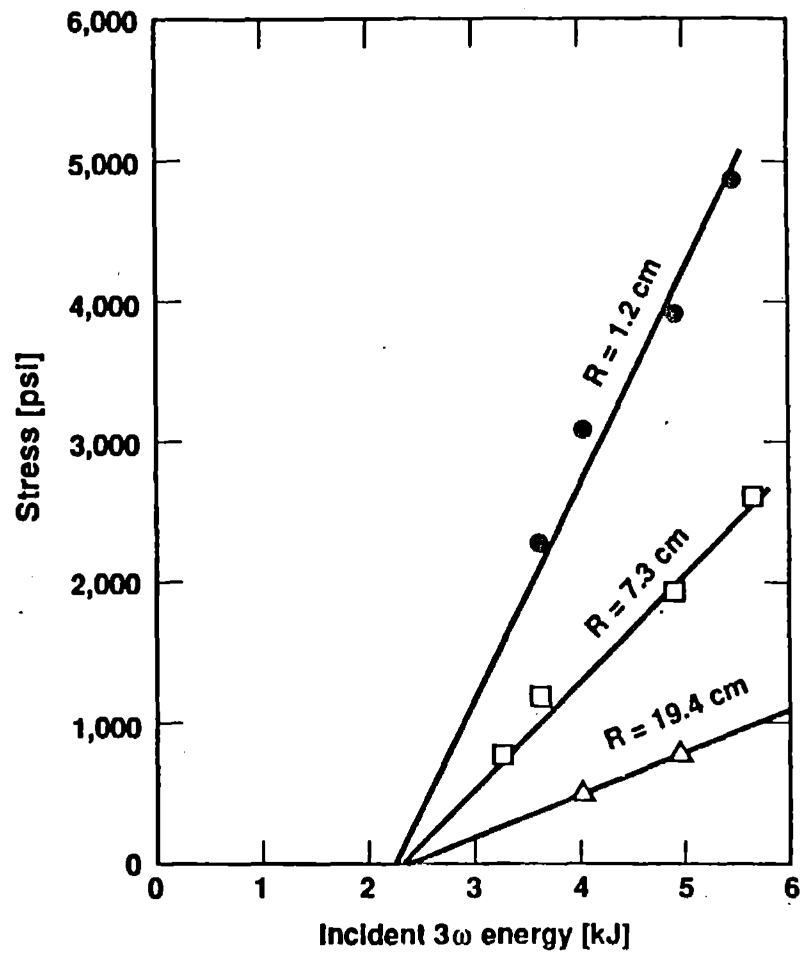

Fig. 3 Peak stress at free surface due to Rayleigh wave.

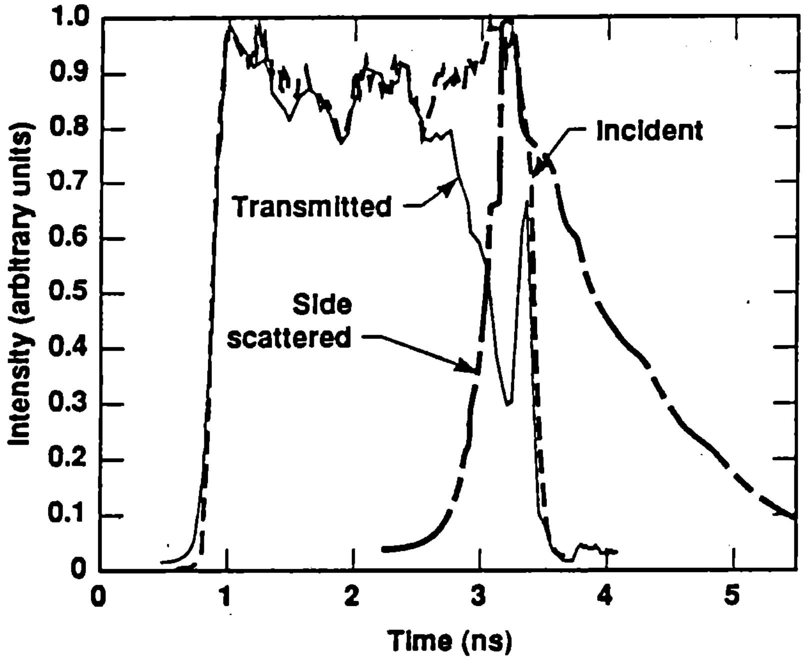

Fig. 4 Incident, transmitted and side scattered 3ω intensity on 5.76 kJ, 3ω shot of 2.35 ns duration.

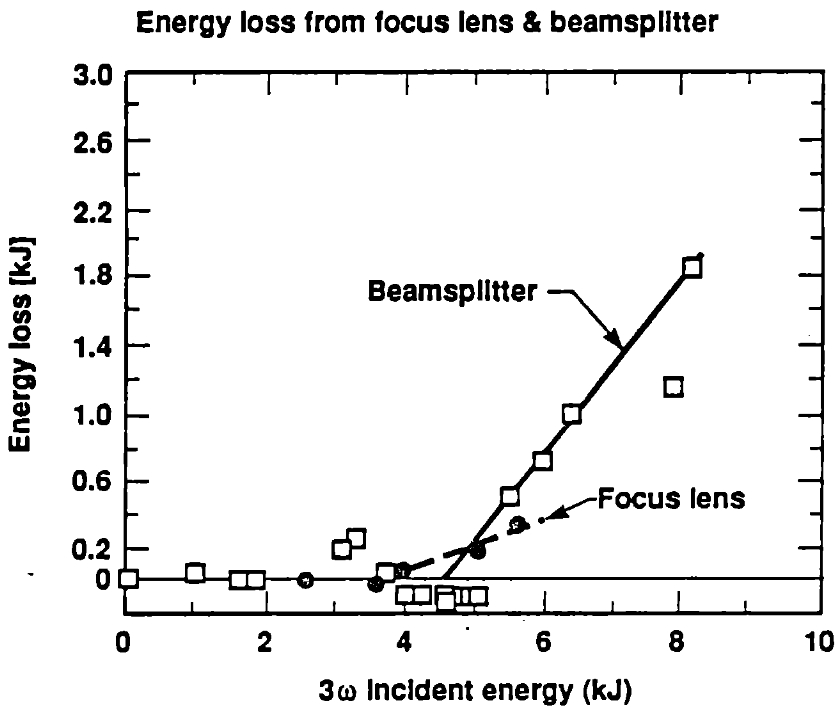

Fig. 5 Energy loss as measured by full aperture calorimetry.

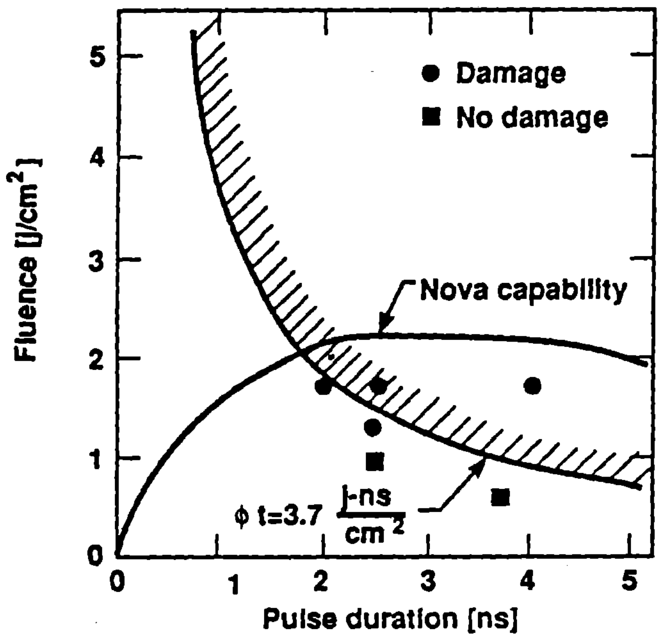

Fig. 6 SBS damage envelope for 351nm in fused silica.

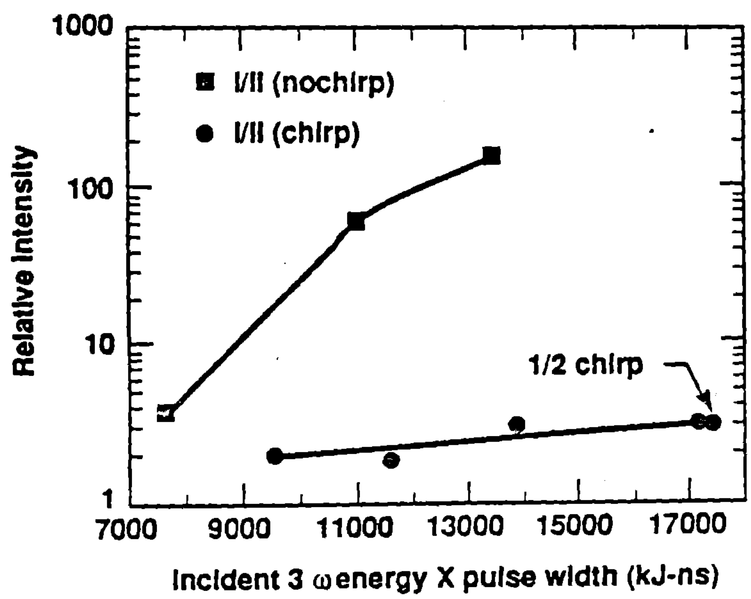

Fig. 7 Peak side scattered intensity from SBS in beamsplitter.

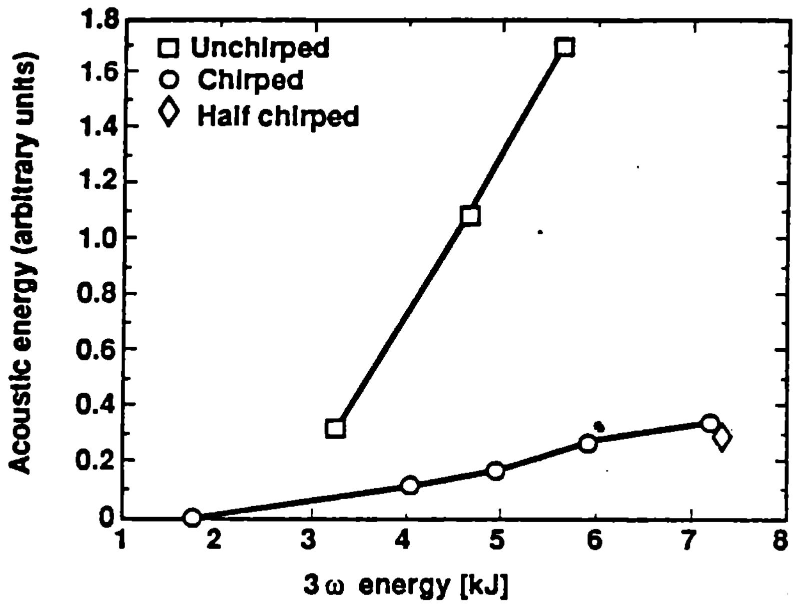

Fig. 8 Influence of chirp on acoustic emission

Table 1

Nova Shot No. (Month/Day/No.)	$E_{3\omega}$ (joules)	I (GW/cm^2)	L (cm)	G (nepers/ns)
32304	4,769	1.603	39.3	4.608
32502	4,775	1.605	39.3	5.420
32504	6,221	2.091	39.3	8.150
50611	7,827	2.631	48.0	9.408
60907	5,723	1.924	48.0	6.859

Gains derived from side scattered light on 2.35 ns shots

Acoustic Damage To Large-Aperture Optics

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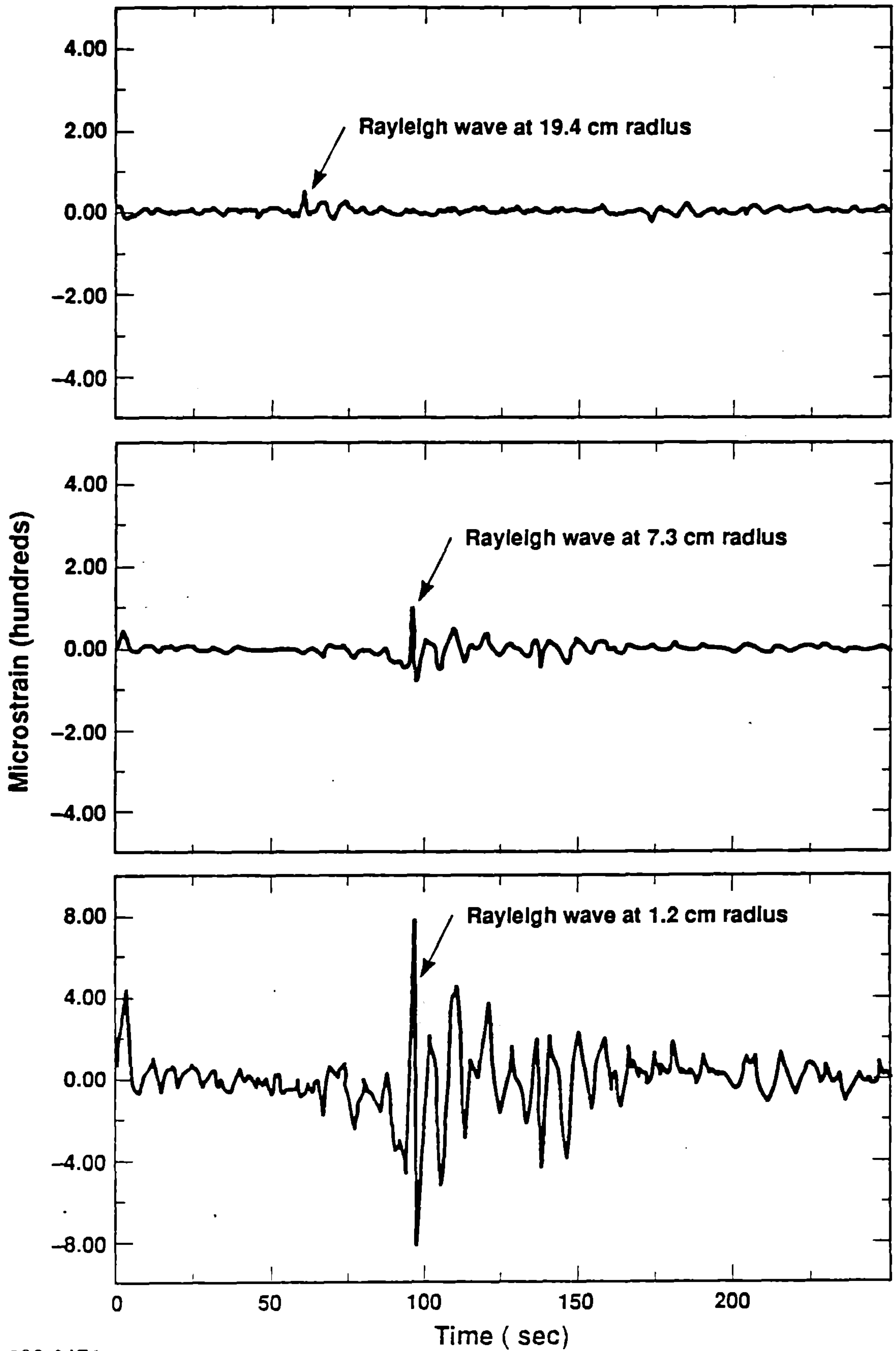
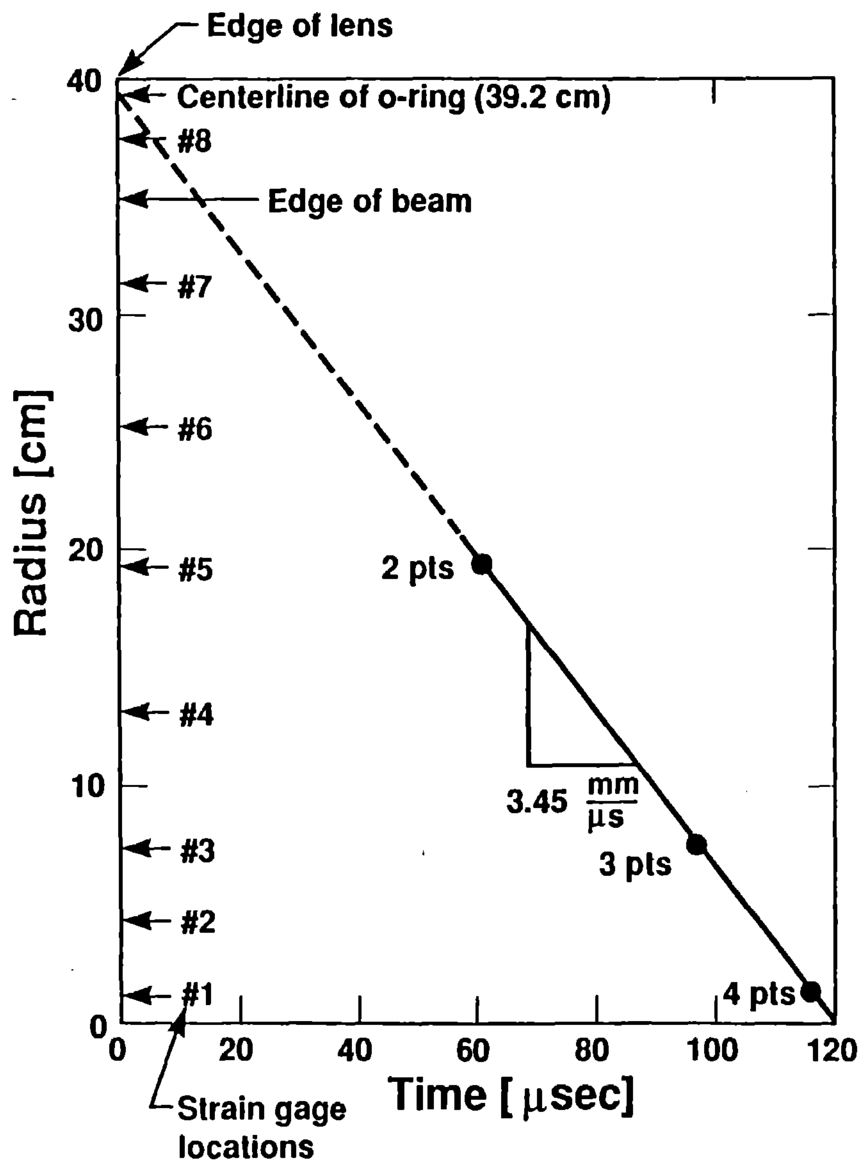
Strain gage signals



Rayleigh wave position–time plot



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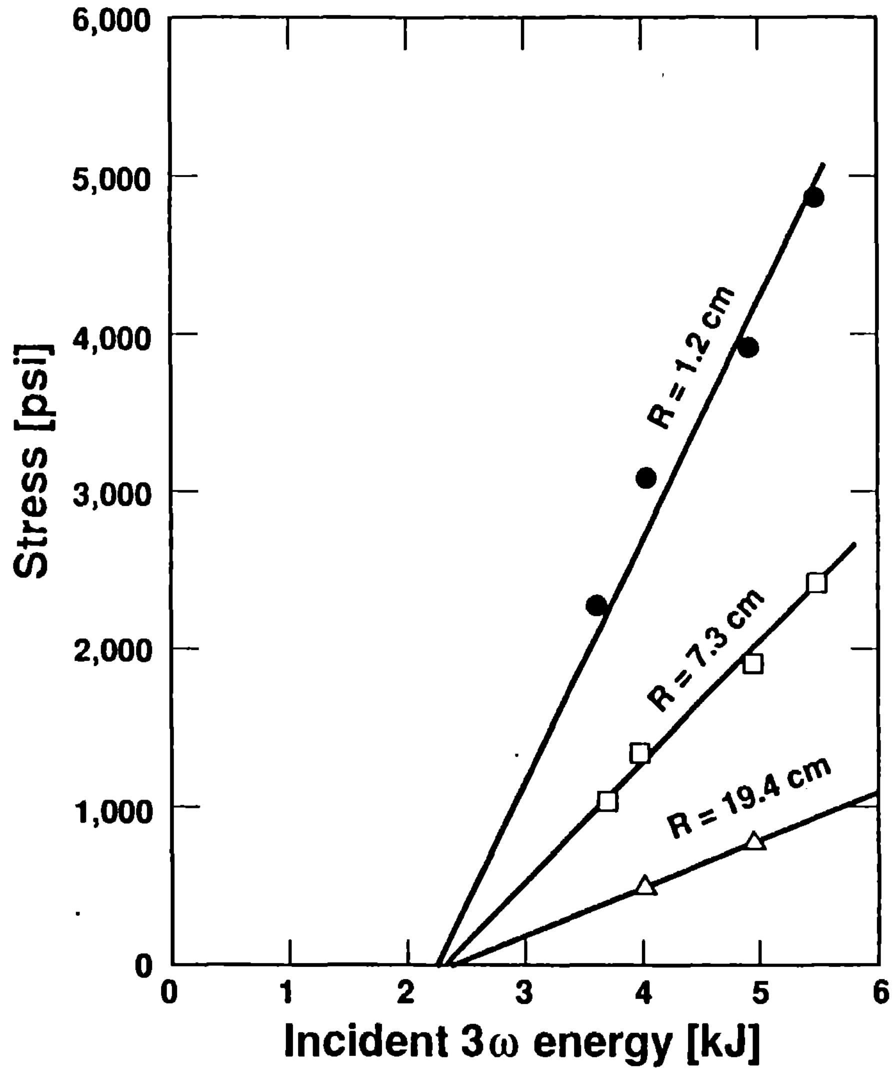
Rayleigh wave peak stress



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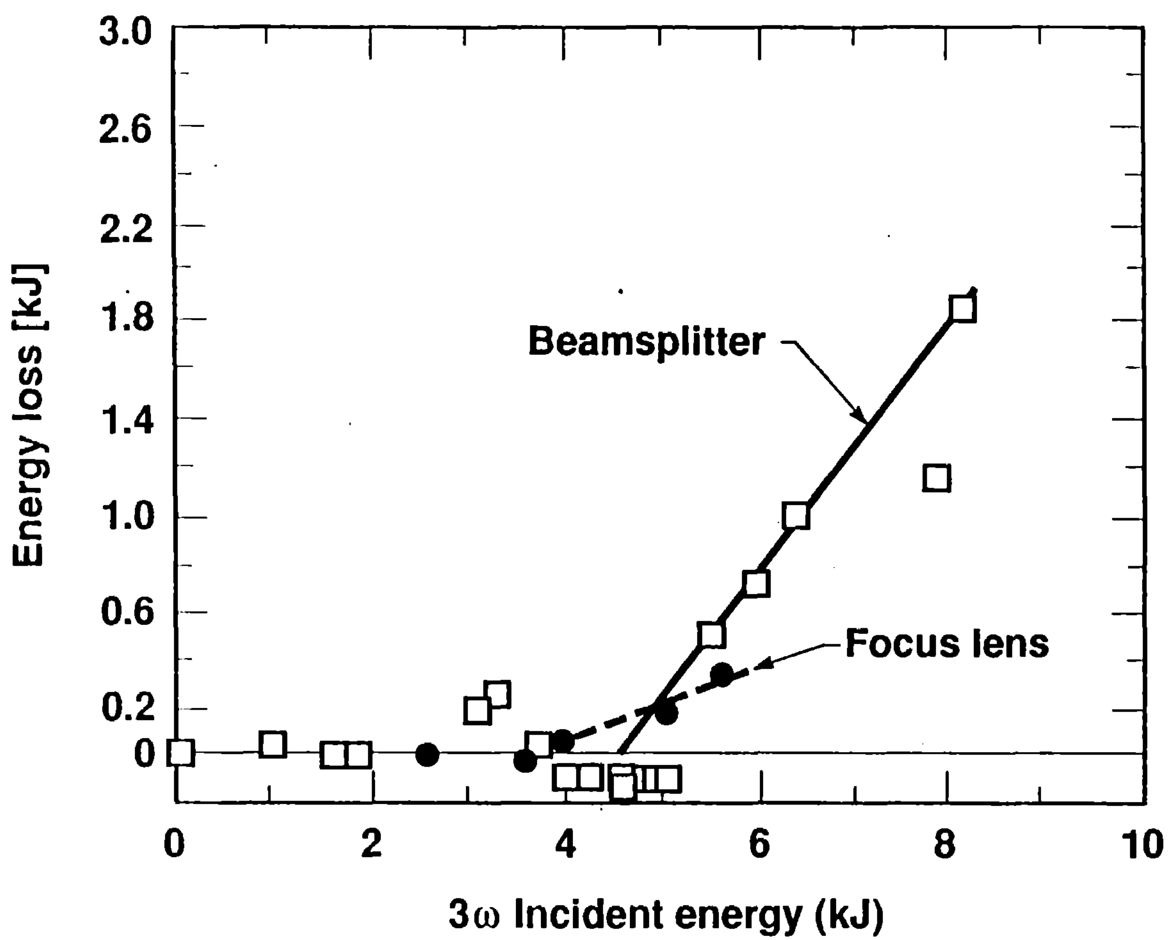
Energy loss from focus lens & beamsplitter



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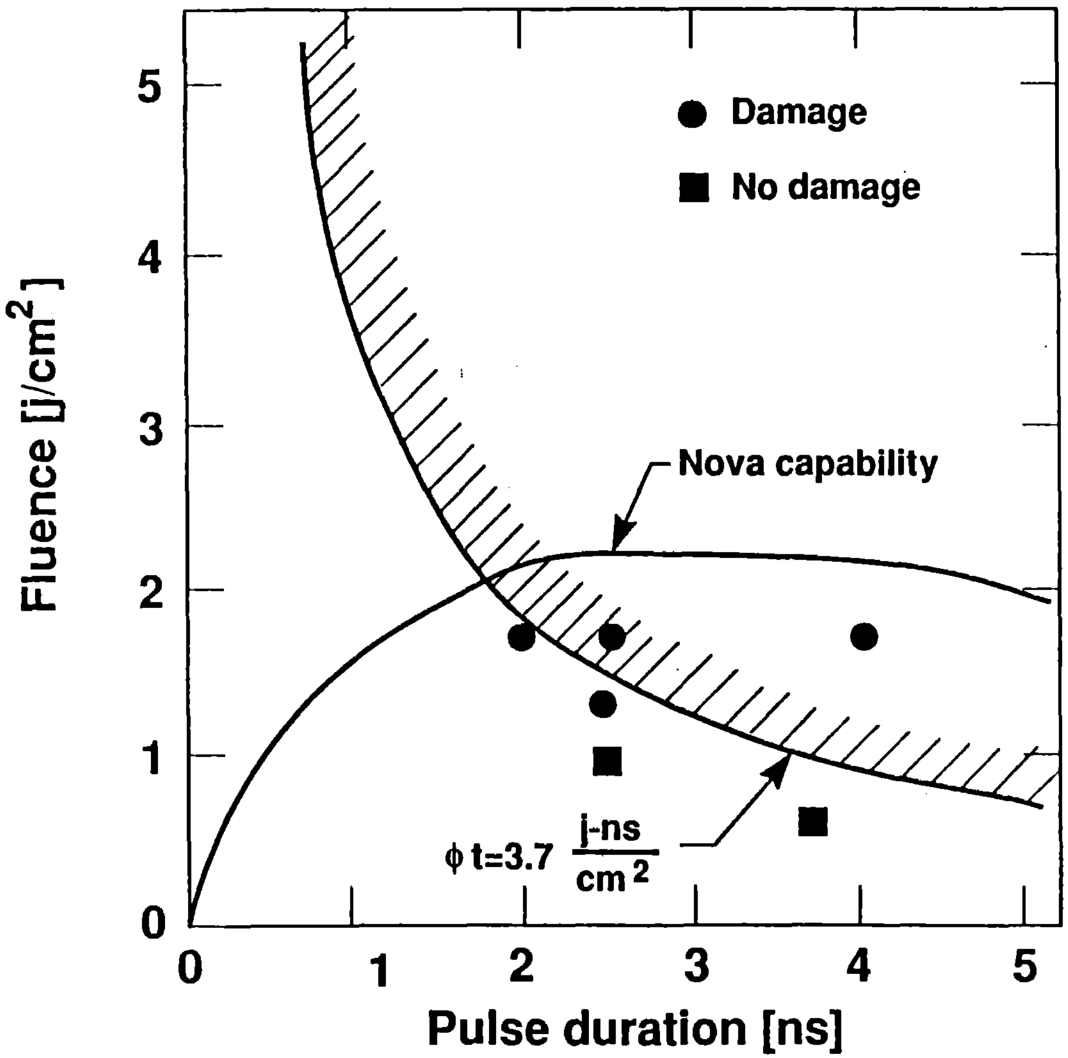
SBS damage envelope for 351 nm in fused silica



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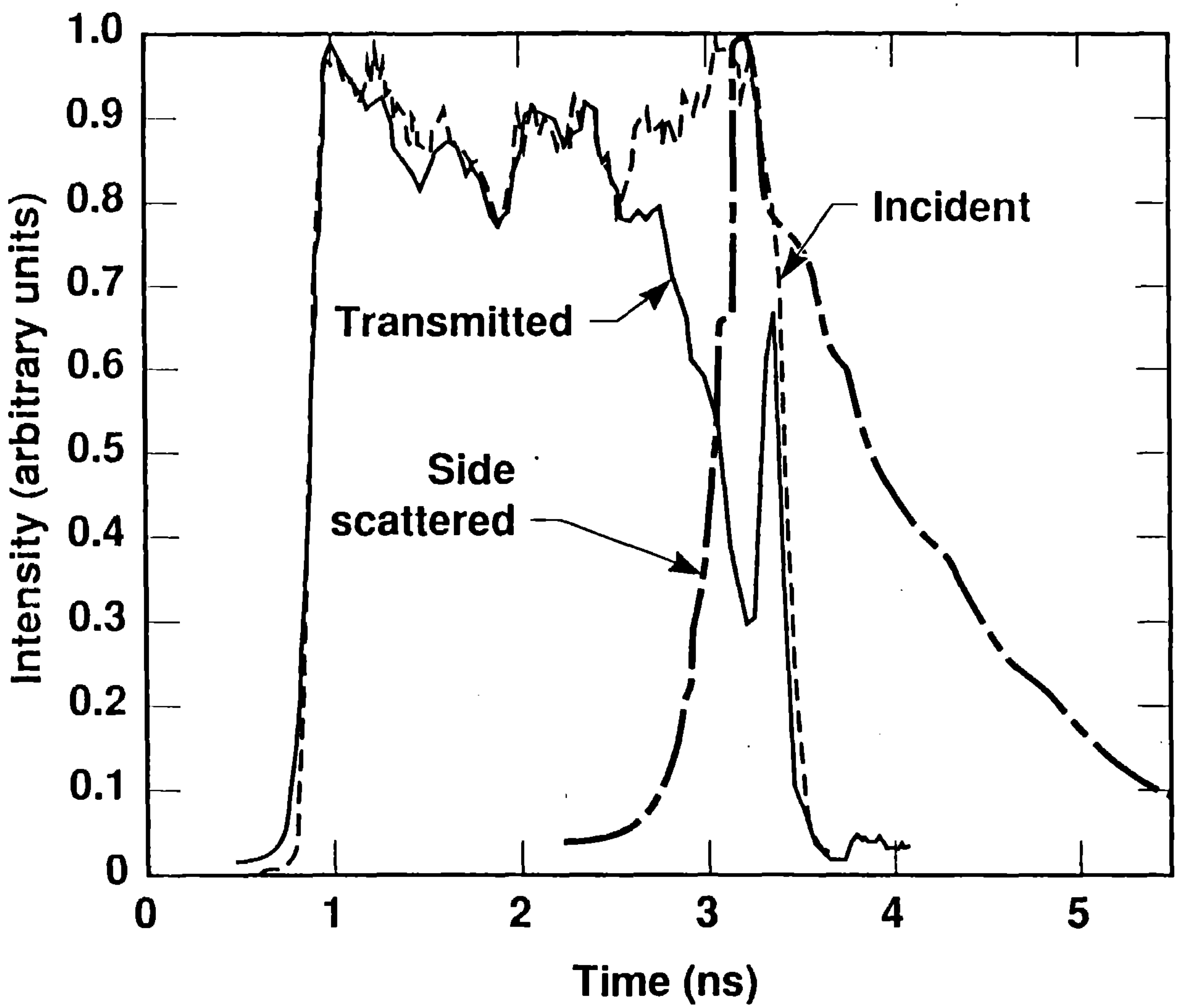
SBS depletion of incident pulse



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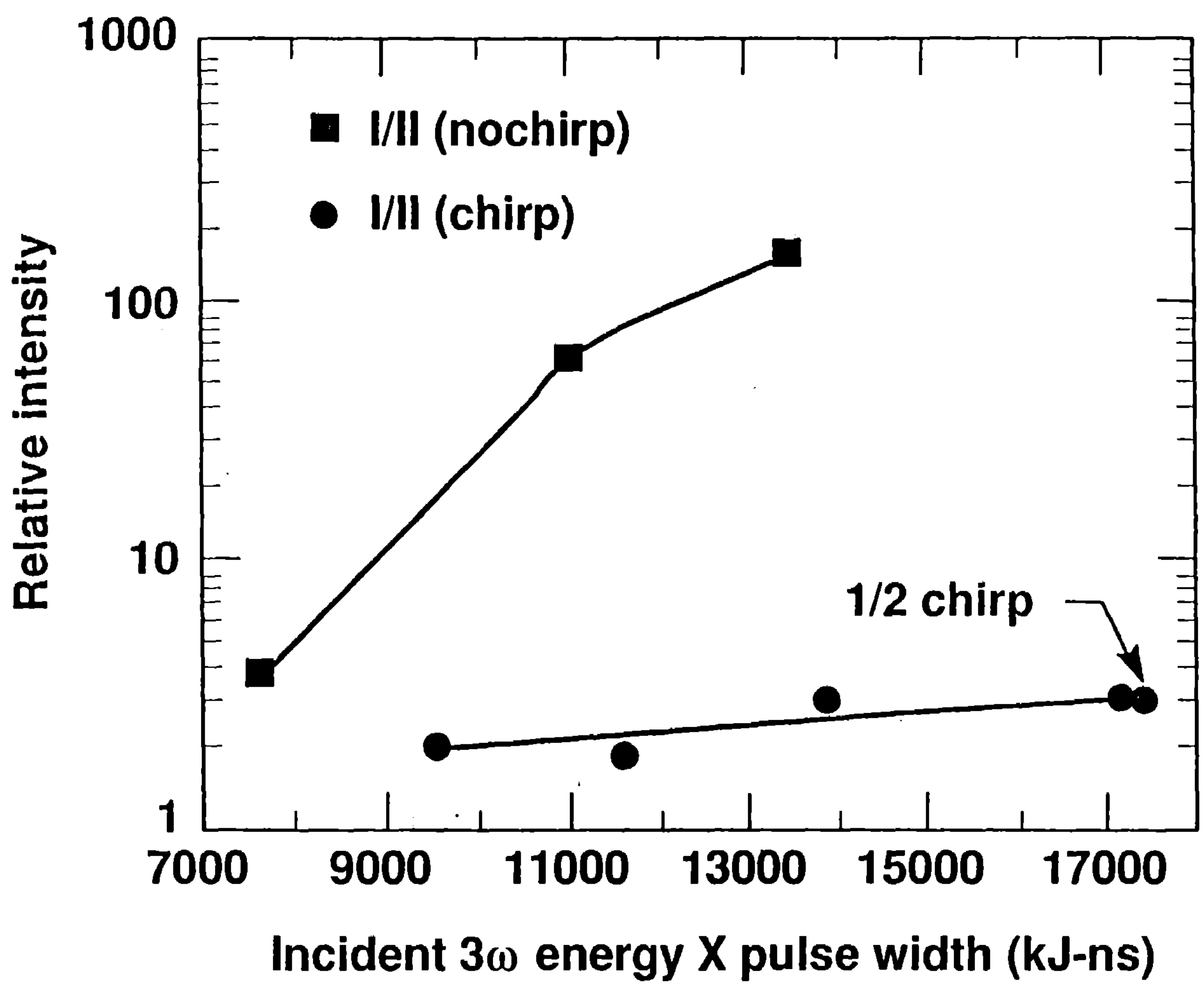
Side scattering from SBS in fused silica



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Gains derived from side scattered light on 2.35 ns shots

Nova Shot No. (Month/Day/No.)	$E_{3\omega}$ (joules)	I (GW/cm^2)	L (cm)	G (nepers/ns)
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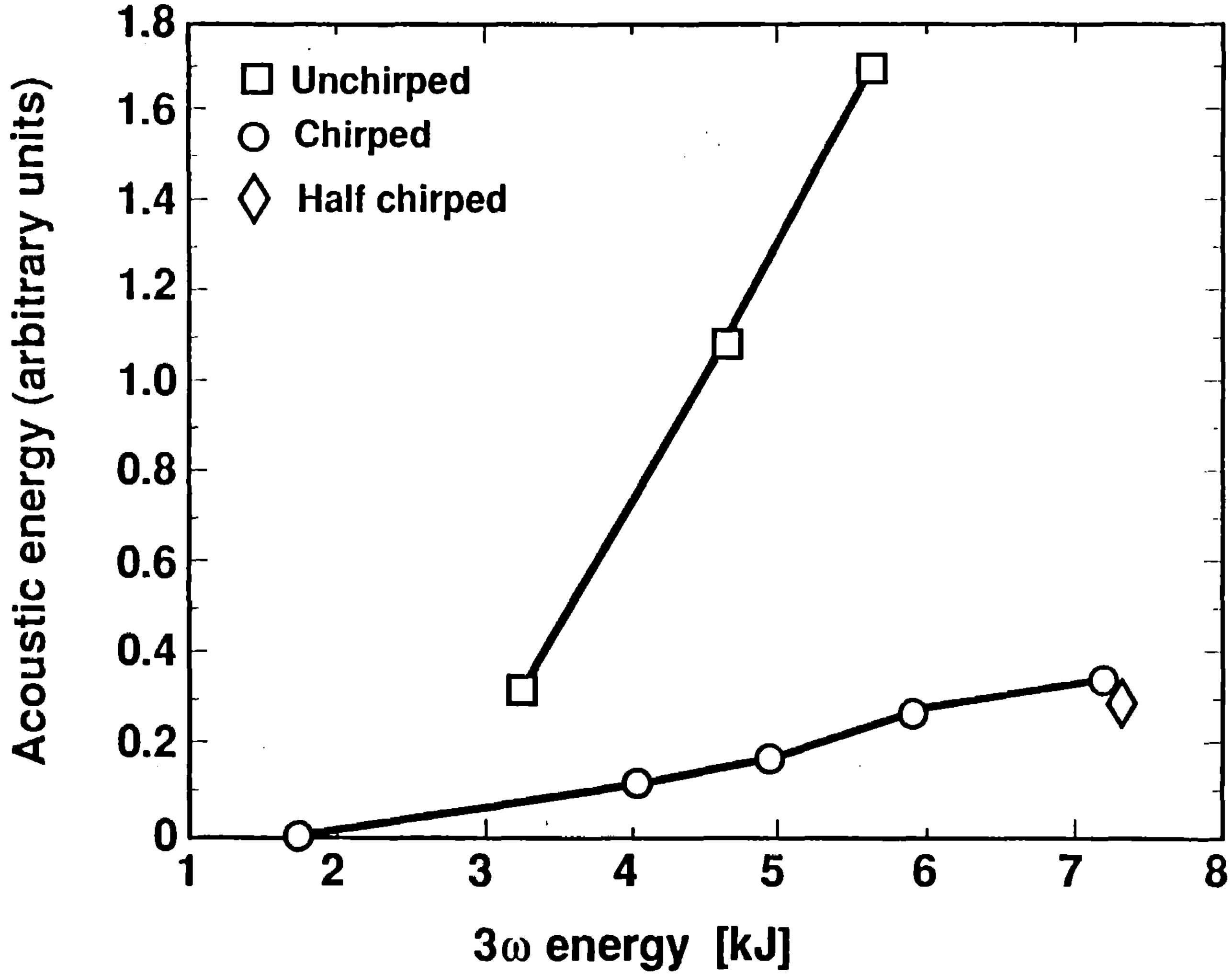
Influence of chirp on acoustic emission



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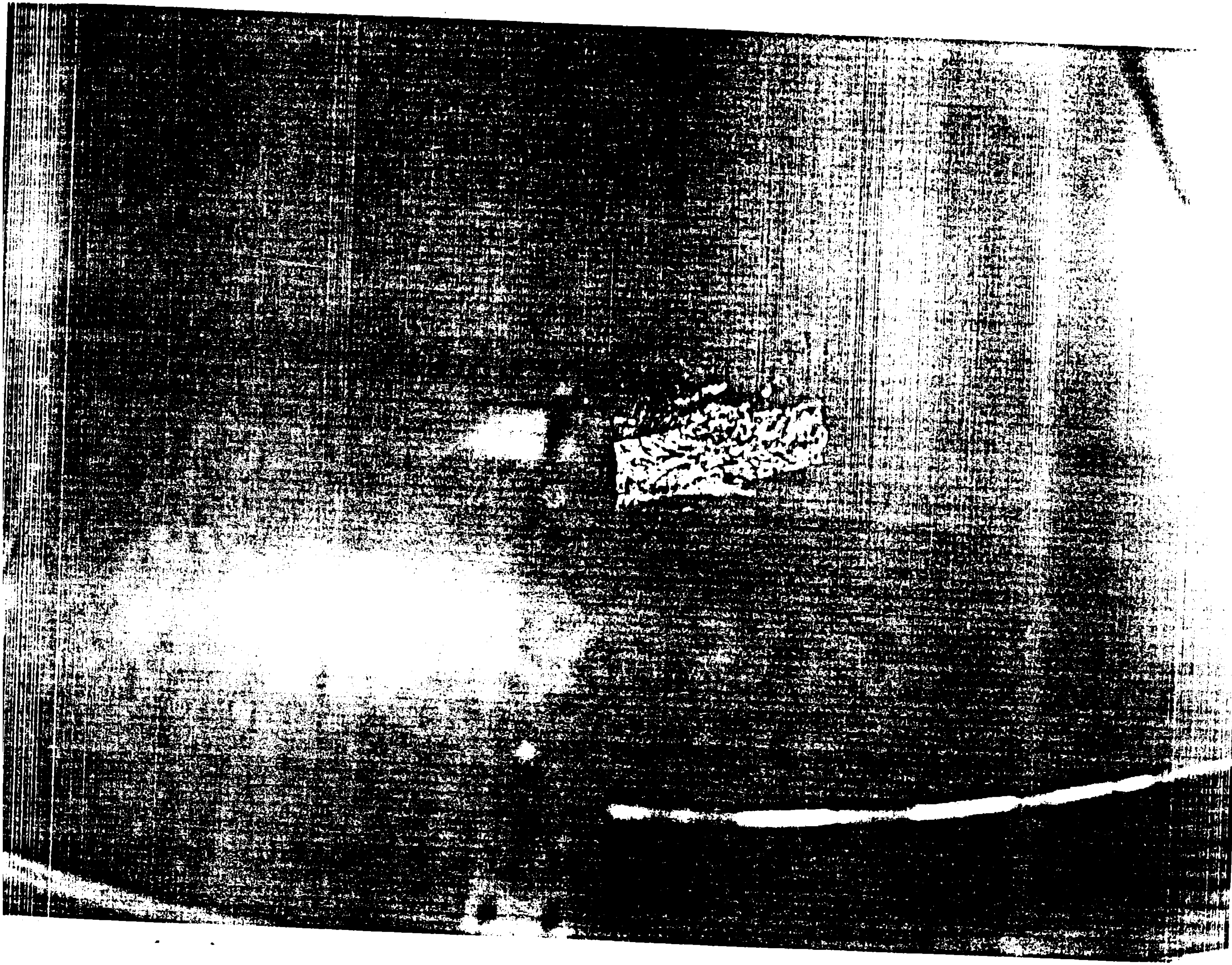

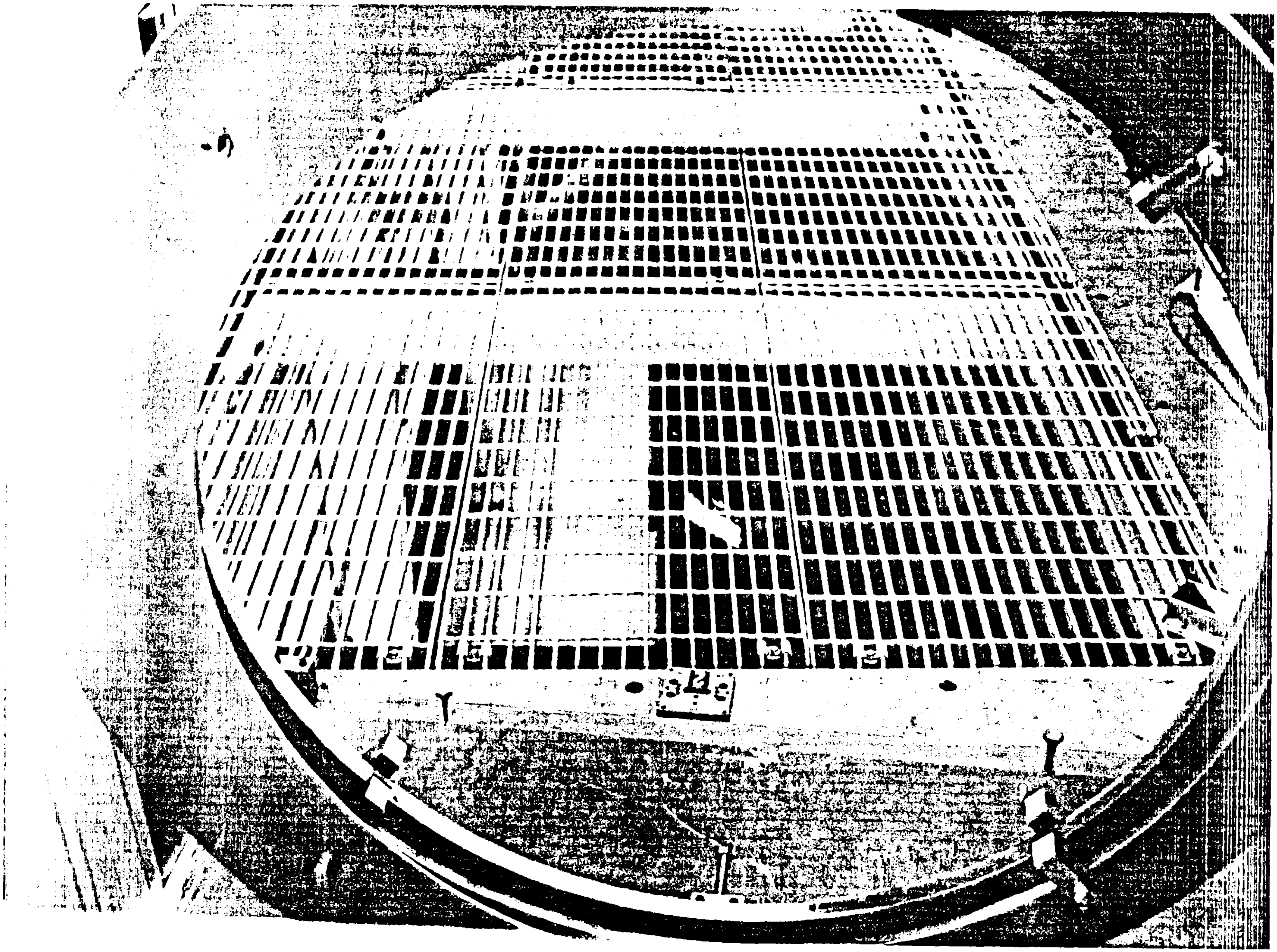

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